THE RELATION OF LEAD-CONTAMINATED HOUSE DUST AND BLOOD LEAD LEVELS AMONG URBAN CHILDREN

FINAL REPORT

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EXECUTIVE SUMMARY

Lead-contaminated house dust was first recognized as an important source of lead for urban children over 20 years ago. In 1992, the United States Congress passed the Residential Lead-Based Paint Hazard Reduction Act, which requires the Environmental Protection Agency (EPA) to promulgate a health-based dust lead standard for residential dwellings based on exposures that are considered dangerous for children.

Objectives

The objectives of this study were: to determine whether dust lead loading ($\mu g/ft^2$) or dust lead concentration ($\mu g/g$) is a better predictor of children's blood lead levels; to investigate whether dust sampling using vacuum methods or a wipe method is more predictive of children's blood lead levels; to identify which interior household surface(s) should routinely be sampled for dust lead measurements; and to estimate the probability of a child having an elevated blood lead level on the basis of a known level of lead in house dust, controlling for other potential exposures.

Methods and Results

Identification and recruitment of eligible subjects was done by using lists of sequential births between March 1, 1991 and September 30, 1992 from three urban hospitals in Rochester, New York. Eligible children were in the 1 to 2½ year age range.

Stringent eligibility requirements were imposed to assure that the child's residential environment was the principal likely source of lead exposure. A cross-sectional study design was employed to investigate the relation of lead-contaminated house dust, other potential environmental sources of lead, and urban children's blood lead levels. Field work was done from August through November 1993.

Three dust collection methods were used to obtain side-by-side samples from as many as 12 sampling locations in each house (i.e., a maximum of 36 samples). Two vacuum methods were used to determine both dust lead concentration and dust lead loading: an in-line filter method (the Dust Vacuum Method), and a cyclone-type sampler with a much higher flowrate (the Baltimore Repair and Maintenance study vacuum method). Wipe sampling, which only measures dust lead loading, was also conducted. Thus, there were five dust collection method variables (Dust Vacuum Method dust lead concentration, Dust Vacuum Method dust lead loading, Baltimore Repair and Maintenance vacuum method dust lead loading, Baltimore Repair and Maintenance vacuum method dust lead concentration, and wipe dust lead loading).

In bivariate analyses, all five dust collection method variables on window sills, window wells and carpeted floors, were significantly correlated with children's blood lead levels. Wipe dust lead loading and BRM loading on non-carpeted floors was significantly correlated with children's blood lead levels.

To determine which of the dust collection method measures was most predictive of children's blood lead levels, all five dust collection method variables were entered into the initial multiple regression model, along with all possible covariates which were significant in bivariate analyses. A backward selection process was used to eliminate non-significant covariates while all five dust collection method variables were simultaneously forced to remain in the model. In addition to the dust collection method, the following covariates were found to be significantly associated with higher blood lead levels among children: Black race, parental reports that children put soil in their mouths, single parent household, and a higher ferritin level.

Each of the five dust collection method variables were then entered individually into separate regression models along with the significant covariates. Dust lead loading using the Baltimore Repair and Maintenance vacuum sampler accounted for the largest amount of variation in children's blood lead levels compared with all other dust collection method variables. The partial correlations for the Baltimore Repair and Maintenance vacuum method dust lead loading and wipe dust lead loading with blood lead was not significantly different. On the other hand, the partial correlation for Baltimore Repair and Maintenance vacuum method dust lead loading and blood lead was significantly different than that for both Baltimore Repair and Maintenance vacuum method dust lead concentration and Dust Vacuum Method dust lead loading.

To determine which types of surfaces (i.e., interior window sills, window troughs (wells), non-carpeted floors, carpeted floors), were the best predictors of blood lead for each dust sampling method, the common covariates were forced into a model and the four surface variables were then allowed to enter through a forward selection process. For Baltimore Repair and Maintenance vacuum method dust lead loading, non-carpeted floors and window troughs were significantly associated with children's blood lead levels, whereas for wipe dust lead loading, non-carpeted floors and interior window sills were significantly associated with children's blood lead levels.

Using logistic regression to adjust for other significant covariates, the proportion of children estimated to have a blood lead level exceeding 10 μg/dL (micrograms of lead per deciliter of blood) was 4.3%, 15%, and 20% at 5 $\mu g/ft^2$, 20 $\mu g/ft^2$ and 40 μg of lead/ft^2 respectively, for non-carpeted floors using wipe sampling. Similar analyses are presented for carpeted floors, window sills and window troughs.

Conclusions

Dust lead loading is a better predictor of children's blood lead levels than is dust lead concentration for the range of lead-contaminated dust and blood lead levels observed in this study. Any household dust lead standard should be linked to the method by which dust is sampled, because the relationship between children's blood lead levels and dust lead levels varies significantly by method of dust collection. The relationship between blood lead levels and household dust lead is different for floors, window sills, and window troughs using the same dust collection method, indicating that different standards are needed for each surface. To determine if a housing unit is safe for children, non-carpeted floors and interior window sills or window troughs can be measured using either the Baltimore Repair and Maintenance vacuum method or wipe sampling method.

Settled, lead-contaminated house dust (at levels observed in this study) is an important contributor of lead to children who have low level elevation of blood lead levels (i.e., blood lead levels up to 20 μg/dL). This study suggests that the proportion of urban children having a blood lead level exceeding 10 μg/dL increases at levels lower than current HUD post-abatement clearance standards and the recently released EPA guidance levels. Future research should seek to confirm the estimated relationship between children's blood lead levels and lead contaminated housedust found in this study. Also, further research should investigate whether dust control is associated with a meaningful decrease in blood lead levels of children at today's lead exposures.

BACKGROUND

The Problem of Exposure to Environmental Lead

Lead poisoning in childhood, once considered an acute self-limiting disease, is emerging as one of the most important chronic health conditions among children in the United States. During the past two decades, evidence has accumulated that demonstrates adverse health outcomes associated with levels of lead exposure previously thought to represent harmless values.[1] These ongoing reductions in the acceptable levels of children's blood lead levels are the result of evidence that previously acceptable low levels are in fact associated with significant adverse sequelae, such as hypertension in adults and among children, lowered intelligence, diminished school performance, and increased rates of behavioral problems.[2-12]

Prior to 1970, significant lead poisoning was defined by blood lead levels greater than 60 µg/dL, a level which was commonly associated with symptomatic illness. Since then, the threshold for defining elevated blood lead levels has gradually been reduced. In 1991 the CDC reduced the threshold even further, to 10 µg/dL.[13]

Children between the ages of nine months and six years are at greatest risk because they have a high degree of hand-to-mouth activity and absorb ingested lead more efficiently, and because of the heightened vulnerability of their developing nervous systems to lead toxicity.[1] Low level lead poisoning, estimated to affect over 20% of American children, has been declared to be "the most common and societally devastating environmental disease of young children" by the U. S. Public Health Service.[10]

Needleman et al found that the rate of severe IQ deficit (i.e., less than 80) was four times greater in children with elevated lead dentine levels compared to those with lower dentine lead levels.[11]
Since that study, the deleterious effects of lead on intelligence have been confirmed in several prospective studies.[3, 4, 12] Bellinger et al showed that blood lead levels at 24 months of age were inversely related to intellectual and academic performance at 10 years of age,[4] and Baghurst et al found a significant inverse relation of IQ scores for both antenatal and postnatal blood lead concentrations in children at 7 years of age.[3] The majority of children who are currently identified to have an elevated blood lead level fall within the range of 10 µg/dL to 20 µg/dL. For these children, it has been estimated that there is 1/4 to 3/10 decrement in IQ point associated with each 1 µg/dL increase in blood lead.[5]

The preponderance of studies show serious deleterious effects of lead on brain function, particularly in very early childhood, and that vulnerability to the adverse neurodevelopmental effects of lead is age-specific. Bellinger et al and Baghurst et al both found that exposure to lead in the preschool age group has a statistically significant effect on IQ,[3, 4] whereas the effect of prenatal lead exposure was not as strongly correlated with children's IQ.[4] These studies suggest that elimination of neurocognitive impairments associated with low levels of lead should emphasize primary prevention, which contrasts sharply with current practices and policies that rely almost exclusively on secondary prevention efforts.

Sources of Environmental Lead

Children are exposed to lead from multiple sources. The most important sources include lead-contaminated paint, dust, soil, and water.[1, 14, 15] Historically, motor vehicle emissions were a major source of airborne environmental lead. Their contribution to children's blood lead levels, however, has diminished since the elimination of leaded gasoline.[1] Paint that was used on both the interior and exterior of houses through the 1950s, and continuing to some extent through the 1970s, often contained high concentrations of lead.[16, 17] Although it is difficult to quantify the relative contributions of various environmental sources of lead, lead-contaminated house dust appears to be a major vector by which children are exposed.[17-20]

In 1974, Sayre et al showed that higher loadings of lead in the dust of inner-city homes were associated with higher dust lead levels on children's hands and elevated blood lead levels in children.[19] Adults living in the same home were not affected, nor were children who lived in suburban residences where dust lead loading was low.[19] The association of lead loading and children's blood lead levels was later confirmed by Charney et al in a case-control study of 49 children.[20] House-dust lead and lead on hands were significantly greater among children with higher blood lead levels (40-79 µg/dL) than among children with blood lead levels below 30 µg/dL.[20] In addition, the lead content of both peeling paint and soil was greater in the homes of children with the higher blood lead levels.[20]

The Cincinnati Prospective Lead Study found a significant positive association of lead-contaminated house dust and children's blood lead levels using a dust vacuum method (Microvac or DVM).[17] Hand-dust lead also was found to be highly correlated with children's blood lead levels.[17] Using structural equation analysis, the investigators showed that lead from soil and lead-based paint both significantly contribute to children's blood lead status. However, lead-contaminated house dust and hand-dust lead levels were found to be more directly and strongly associated with blood lead levels.[17]

Dust control has been shown to be effective in reducing children's blood lead levels. In a randomized trial of the efficacy of a dust-control intervention on children with blood lead levels between 30 µg/dL and 49 µg/dL, Charney et al found a significant reduction in blood lead levels of children in the experimental group after 12 months.[21] The decline in blood lead was greatest for children who had the highest blood lead levels.[21] The effectiveness of dust control has not been demonstrated at blood lead levels below 30 µg/dL.

Studies have found that soil lead concentration is correlated with children's blood lead levels. In a longitudinal study of 249 children, Rabinowitz et al found that the lead levels in outdoor soil were a strong predictor of children's blood lead levels.[15] In a recently completed study, Weitzman et al reported a statistically significant decline in blood lead levels among children who lived in homes that received soil abatement.[22] Nonetheless, because the decline was modest, the authors concluded that soil abatement is not likely to be a useful clinical intervention for the majority of urban children.[22]

Control of Environmental Exposure to Lead

The recognition that low-level exposure to lead is a significant hazard has preceded the development of standards and interventions to prevent exposure to lead. Two states (Massachusetts and Maryland) and the Department of Housing and Urban Development (HUD) have adopted post-abatement dust lead standards of 200 µg/ft² for floors, 500 µg/ft² for window sills, and 800 µg/ft² for window wells using a wipe method. More recently, the Environmental Protection Agency adopted guidance levels that are the same as HUD post-abatement clearance standards with the exception of floor dust lead levels, which were lowered to 100 µg/ft². However, these standards and guidance levels are based on limited data. To date, studies that have measured the relation of children's blood lead levels and dust lead levels often have lacked power, included children who may have had exposure elsewhere or who had extremely high blood lead levels, or used dust collection methods that have not been standardized.[23]

Despite evidence which suggests that environmental interventions can be efficacious, some abatement practices have a limited duration of effect and can actually increase the amount of lead dust available to children and their risk of lead toxicity.[24-26] Case studies suggest that abatement of lead-contaminated paint can actually exacerbate the problem and increase children's exposure if dust lead levels are inadequately controlled.[24-26] An improved understanding of the relationship between lead-contaminated dust and children's blood lead levels, and the identification of a dust lead level that is dangerous, should begin to shift the public health emphasis toward primary prevention and provide assurance that interventions which are intended to reduce potential sources of lead in children's environments do not cause an increase in lead-contamination of dust.

Background for the University of Rochester Lead-In-Dust Study

In 1992, the United States Congress passed Title X, the Residential Lead-Based Paint Hazard Reduction Act. Under section 403 of Title X, the Environmental Protection Agency (EPA) is required to promulgate a health-based dust lead standard for residential dwellings. Levels are to be established for exposure to lead in interior house dust that are dangerous for children. However, there is currently limited data to inform the EPA about what level of lead-contaminated house dust is dangerous to children. It is also unknown whether dust lead loading (µg/ft²) or dust lead concentration (µg/g) is more predictive of children's blood lead levels; which dust collection method should be used; and which surfaces to sample.

The levels of lead in dust that are dangerous to children are poorly defined. Duggan and Inskip concluded that children's blood lead concentrations increase about 5 µg/dL for each 1,000 µg/g increase in household dust lead levels.[23] But they also found that there was a wide range in the estimated increase, from 1 to 10 µg/dL for every 1000 µg/g increase in dust lead levels. The wide range is due to many factors, including the various methods of sampling dust, lack of criteria to eliminate other sources of lead exposure, the locations within the house that were sampled, and the ages and consequent behaviors exhibited by the children who were studied. Many of these difficulties can be resolved by designing a study of a well-defined age group and by using a standardized dust collection method and protocol.[23]

Over 10 methods have been used to sample dust, but each has certain limitations. Ideally, any dust collection method that is chosen by the EPA should fit the following criteria:

1. produce measurements that are correlated with blood lead levels of children who are at risk;
2. be relatively inexpensive;
3. be easy to use;
4. be easy to transport;
5. be usable on various types of surfaces (e.g., wood, carpet) which may be in poor condition;
6. be reliable;
7. impose minimal burden on the occupants.

In response to the limited data, the Lead-In-Dust Study at the University of Rochester was developed by the National Center for Lead-Safe Housing, in collaboration with the U. S. Department of Housing and Urban Development, the Centers for Disease Control and Prevention, and the Environmental Protection Agency. The purpose of the study was to:

1. determine the relation of lead loading and lead concentration of house dust with blood lead levels among urban children;
2. develop a predictive model to determine the risk that a child will develop an elevated blood lead level on the basis of a known level of lead in house dust; and
3. determine, for carpeted and non-carpeted surfaces, whether measurements using a vacuum method or wipe method are more highly correlated with children's blood lead levels.

STUDY DESIGN

The Lead-In-Dust Study employed a cross-sectional design to investigate the levels of lead in house dust and other potential environmental sources of lead, and blood lead levels among urban children.

Sample Size Calculations

Data to calculate the necessary sample size for this study were limited. Rabinowitz et al obtained an estimated Spearman correlation between interior dust lead loading and blood lead levels of 0.31 to 0.48 for children 1 to 24 months of age.[15] Thus, it was reasonable to expect Pearson correlation coefficients of similar magnitude between log(BPb) and log(Dust Pb) in this study. A sample size of 200 in the Lead-In-Dust Study provided a power of greater than 99% to detect a Pearson correlation of .30 (or greater) at the .05 significance level.

Eligibility Criteria

Children ages 12 to 30 months who resided in the same house since 6 months of age, lived in the city of Rochester, spent a limited duration of time away from their primary residence ($\leq$ 20 hours/ week), and had no known prior history of medical treatment or an environmental intervention for an elevated blood lead level were eligible for the study. Children were excluded from the study if they had taken a prescribed iron supplement in the past 2 months or if there had been major renovation of their residence during the past 12 months. Major renovations were defined as sanding or scraping more than 1 interior wall; sanding or scraping more than 1 ceiling or floor; or replacement of more than 2 window frames. Finally, if any adult who lived in the household was employed in an industry or involved in a hobby that involves exposure to lead, the child was not eligible.

Eligibility criteria were selected to maximize our ability to assess the independent relationship of settled lead-contaminated house dust and children's blood lead status. Only children who were between the ages of 12 to 30 months, the age of greatest risk for lead exposure, were eligible. In a few instances, children who were 30 months of age at the time of enrollment turned 31 months of age prior to the field sampling. These children were retained in the study. Other eligibility criteria described above were employed to minimize lead exposure from sources other than the child's primary residence. Thus, children who spent more than 20 hours away from their home each week or who lived with an adult who was exposed to lead from an occupational or recreational activity were excluded. Similarly, children were ineligible if they or their environments underwent recent interventions that were likely to alter the blood lead and dust lead relationship, e.g., major renovation, recent ingestion of prescribed iron products, or any medical or environmental intervention for an elevated blood lead level.

Changes in Study Design

There were several changes made between the time the study was awarded to the University of Rochester and its implementation. Initially, the study design did not include a random sample or stratified enrollment. The Lead-In-Dust Study Group decided to develop a random sample of sequential births using birth registries from 3 urban hospitals. We also attempted to use stratified enrollment to ensure adequate representation of children who are at risk for exposure to lead (i.e., enrollment of children who were equally distributed across the 18-month age range, with at least 70% of families having an annual income below $15,500 and living in houses built before 1940). However, it became apparent after approximately 50% of the sample was enrolled that it was necessary to enroll all children who were eligible in order to develop an adequate sample size. Therefore, the stratification scheme was eliminated. Nevertheless, a significant proportion of children who were enrolled exhibited the characteristics described above.

Changes in dust collection and other protocols were also made during the planning phase of the study. Because both vacuum methods, the Baltimore Repair and Maintenance (BRM) sampler and the Dust Vacuum Method (DVM), appeared to have advantages and disadvantages, it was decided to use three rather than two methods: the BRM, the DVM, and the wipe method. Also, since earlier studies found that hand dust lead was significantly correlated with children's blood lead levels, we decided to perform hand wipes of children's hands as an additional measurement of children's lead exposure.

Changes also were made to the dust sampling reliability protocol. Because of the limited number of floors and windows, and the extensive burden to respondents, we limited the reliability sampling to 3 floors, 2 windows, and repeated x-ray fluorescence (XRF) measurements in 10% of the dwellings. Finally, to measure variability of recovery of dust lead collection between technicians, an in-lab reliability study was added, using a known amount and concentration of lead-contaminated dust on three types of surfaces.

We also modified or added several new laboratory analyses to the study protocol. Dust samples that had undetectable lead levels by flame atomic absorption (i.e., $< 6\ \mu g$/sample), were assayed using graphite furnace atomic absorption analysis. Finally, we added soil sieving to the protocol so we could measure and correlate children's blood lead levels with soil lead concentration of both the total fraction (coarse-sieved soil) and urban soil fraction (fine-sieved soil).

Human Subject Research Approval

Approval for the study was received from each of the 3 hospitals involved in the study (Rochester General Hospital, St. Mary's Hospital, and Strong Memorial Hospital), from the Monroe County Health Department Investigational Review Board, and from the Office of Management and Budget (OMB approval number, 2539-0003, expiration date December 31, 1993).

METHODS

Recruitment and Enrollment

Identification and recruitment of eligible subjects was done by using a random sample of sequential live births from 3 urban hospitals. We obtained birth registry data for all live births between March 1, 1991 and September 30, 1992 from Rochester General Hospital, Strong Memorial Hospital, and St. Mary's Hospital. After the combined list was checked for errors and duplication, the order of the entries on the list was randomly permuted (using the SAS random number generator RANUNI) to obtain the sampling frame.

Children in the sampling frame were matched by birth date, name of child, and mother's name with medical billing information from inpatient and outpatient services for the 3 hospitals and for 4 inner-city clinics that provide the majority of care to families who live in the inner city of Rochester. A list of children who are recipients of social services from Monroe County Department of Social Services and who were born between March 1, 1991 and September 30, 1992 was also used to obtain current addresses and phone numbers of those in the sampling frame. Finally, we also obtained addresses for children in the sampling frame from data provided by the Monroe County Health Department Lead Poisoning Prevention Program and by respondents in churches and clinics in the city of Rochester. Due to a delay in human subject research approval, St. Mary's Hospital birth registry data was received after enrollment was underway. These data were merged with the sampling frame using a similar random permutation.

To determine eligibility and collect demographic data, interviewers contacted families by telephone. Each telephone number identified was called systematically until it was either resolved or until at least 6 calls were made. The telephone protocol required a minimum of two attempted calls in the morning, two in the afternoon, and two in the evening. Once families were contacted and were determined to be eligible, they were invited to participate in the study. Prior to the field visit, the Enrollment Coordinator called to confirm the scheduled appointment and confirm eligibility. Completion of the eligibility checklist prior to study entry lessened the possibility of ineligible subject entry.

After a family agreed to participate, an environmental health team visited the home, obtained a venipuncture blood sample from the child, conducted an interview, visually inspected the home for various sources of lead, and obtained environmental samples. Families received $50 gift certificates after collection of all environmental and blood samples was completed. In addition, the blood lead and ferritin results were reported to the families and their children's designated primary health care providers, along with an interpretation of the findings. Enrollment of families was done from August 27, 1993 to November 18, 1993 and environmental sampling was conducted from August 29, 1993 to November 19, 1993.

Outcome Measurement

Children's blood lead levels are the main outcome measurement. Venous samples for children's blood lead and ferritin levels were obtained by certified pediatric phlebotomists during the home visit using lead-free containers provided by the New York State Department of Health Clinical Laboratory Evaluation Program. Techniques were used to ensure that we obtained blood with minimal extraneous lead contamination. Blood lead was determined using Electrothermal Atomization Atomic Absorption Spectrometry (Graphite Furnace AAS). All blood lead results reported are the means of three separate analyses, each carried out on three consecutive days, for a precision of ± 1 μg/dL and a lower detection limit of about 1 μg/dL. Children who were found to have a blood lead level greater than 20 μg/dL were referred to their providers for further evaluation and to the Monroe County Health Department for a follow-up environmental inspection.

Child Characteristics

A behavioral questionnaire was used to assess factors that bear on a child's contact with various sources of lead. We used a modified version of the questionnaire that was developed and used in the recently completed Boston Lead-in-Soil Study.[22] The survey was developed by the Boston investigators, in collaboration with the Centers for Disease Control and Prevention. The questionnaire collected information to characterize each child's exposure to lead in soil and household dust. Respondents were asked to identify the child's outside play areas, the amount of time spent away from home (e.g., day care), and use of vitamins. Information about a child's tendency to suck his or her fingers or thumb, or put soil or paint chips in the mouth, and about handwashing after playing outside and before eating was also collected as part of the interview.

Household and Family Characteristics

An initial survey was filled out at the time of enrollment to determine eligibility. During the time of the environmental visit, the eligibility survey was verified for address, duration of residence at the address, and other inclusion criteria. Each guardian was then interviewed to identify the type and frequency of cleaning, any minor renovation or painting in the dwelling, and the use of ceramic pottery or folk medicines. Other information that was obtained included the level of education, occupation, race, income level, marital status, and age of the parent. Smoking among members of the household and type of health insurance were also documented.

Dust Lead Measurements

Household dust sampling was conducted to characterize the potential exposure of children to lead from environmental dust, including lead loading ($\mu g/ft^2$) and concentration ($\mu g/g$). In each housing unit, we attempted to collect a total of 36 interior dust samples and 2 exterior dust samples from surfaces that were most accessible to the child (i.e., floors and interior window sills) and those known to be heavily contaminated with dust lead (window wells or troughs).

Three dust collection methods were used to sample house dust. Two vacuum methods were used that measure both dust lead concentration and dust lead loading: the Dust Vacuum Method (DVM)[27] and the Baltimore Repair and Maintenance vacuum method (BRM).[28] A wipe sample, which only measures dust lead loading, was also obtained. The BRM sampler, a modified, portable version of the HVS-3 cyclone sampler, is a high flow vacuum that employs a Dirt Devil® vacuum. The BRM does not have a specified flow rate and therefore is not calibrated, but its flow rate is reported to be approximately 16 liters per minute by the Baltimore investigators (Farfel M, personal communication). In contrast, the DVM (or Microvac) uses a portable personal air sampler that has a low air flow rate of 2.5 liters/minute and an in-line filter. Finally, for wipe sampling we used a commercial brand of "Little Ones" baby wipes (K-Mart), a non-analytic grade material.

Wipe Sampling

For each sample collected, a new non-powdered disposable glove was donned. Before wiping, the wipes were inspected to determine if they were moist. The wipe was opened and placed on one corner of the surface to be sampled. With the fingers together, the wipe media was passed over the entire surface in a right to left direction, using a "S" motion, pressing firmly but not excessively with the palm. The wipe was then folded in half with the contaminated side facing inward and passed over the entire surface in a top to bottom direction. The wipe was then folded with the contaminated side facing inward and inserted, without touching the sides, into a non-sterilized clean 50 ml polypropylene centrifuge tube.

Dust Vacuum Method Sampling

A personal air sampler was calibrated at 2.5 liters/minute against a primary standard with a mixed cellulose ester filter (0.8 µ pore size) in line. The sampling train consisted of a piece of ¼" I.D. Tygon tubing attached to the pump and a 37 mm filter cassette. A brand new piece of ¼" I.D. Tygon tubing measuring no more than 1" in length was attached to the inlet of the cassette. The open end of the Tygon tubing was cut at about 45° angle, the surface was vacuumed with contiguous, non-overlapping left-to-right strokes by pressing the end of the tubing on the surface and drawing it across the sampling area in strokes lasting approximately 1.5 seconds each. The vacuuming process was then repeated in a top to bottom motion, and then a third time in a right to left direction. Three passes were made over the surface to be sampled.

Baltimore Repair and Maintenance Vacuum Sampling

After the BRM was cleaned and assembled, a clean pair of powderless gloves were used to handle tared Teflon PFA liners to capture the dust. A Dirt Devil vacuum cleaner hose and clean inlet were used in a left-to-right motion, followed by a front-to-back motion over the entire area designated for sampling. After exactly two minutes, vacuuming was ended.

Each dust collection method was used to collect side-by-side samples in each household from the following locations: the participant child's bedroom window well, interior window sill, and floor; the kitchen window well and floor; the window well, interior window sill, and floor in the child's principal play area; the interior window sill and floor in the living room; the entryway floor; and the porch floor. The porch sample was included with the interior dust measurements for statistical analysis.

Disposable templates measuring 1 foot by 1 foot were used to define the floor area to be sampled, and masking tape was used to construct the templates for window wells and window sills. Each interior sill or well was divided into thirds of approximately equal size. Grooves and indentations at the two sides of the window sills and window wells were not included in the sample.

For each sample set collected, the wipe sample was collected first, followed by the DVM, and finally, the BRM. This sequence was used to minimize contamination caused by air exhaust of the vacuum methods. The location of the sampling methods with respect to each other (i.e., the template pattern) was determined for individual windows and floors by using lists of random numbers. Therefore, the wipe method had an equal chance of being used to collect dust from the corners of the window well or sill as the DVM or BRM.

The midpoint or largest area in the room was selected for floor sampling, unless the child had a specific play area in the room. In that case, the play area was sampled. All floor samples obtained within each room were from the same type of surface (e.g., carpet, tile, wood). In the event the DVM did not collect enough dust from an interior window sill, a second area was sampled from a comparable interior window sill in the same room, if available.

We also obtained one exterior dust samples for each of the two vacuum methods from a sidewalk, driveway, or a paved surface on the premises. The surfaces sampled were the areas most accessible and played on by the child.

All dust samples were digested using EPA method SW846-3051 and analyzed by either flame or graphite furnace atomic absorption spectroscopy using EPA method 239.1 or 239.2, respectively. The detection limit using flame atomic absorption was < 10 µg/sample; for graphite furnace, the detection limits for wipe, BRM, and DVM samples were < 0.25 µg/sample, < 0.15 µg/sample, and < 0.15 µg/sample, respectively. All samples were first analyzed by flame atomic absorption, followed by graphite furnace if levels were below detection limits for flame atomic absorption. Field blanks were inserted into the sample at a rate of one per sampling method for every 5 housing units sampled. Control samples (sampling media or containers fortified with a known amount of lead) were inserted into the sample stream at a minimum rate of 1 per 10 samples analyzed.

Other Environmental Lead Measurements

Paint Measurements

Ten to 15 measurements of the lead content of interior and exterior painted surfaces were made for each housing unit using a portable x-ray fluorescence analyzer (Microlead I, Revision IV, Warrington). For each housing unit, at least one measurement was obtained from the kitchen, the child's bedroom, the principal play area of the child, the entryway, and the exterior surface of the housing unit. All surfaces with deteriorated paint were measured in addition to these surfaces. At each location, 3 readings were made and then averaged. The XRF calibration check was done prior to measuring each housing unit. During the first 3 weeks of the study, a Microlead standard (4.2 mg/cm^2) was used. Thereafter, the Level III NIST 2579 (1.02 mg/cm^2) standard was used for the remainder of the study. The upper detection limit of the Microlead I is approximately 40 to 50 mg/cm^2 and it is difficult to resolve a low positive lead level of less than 0.5 mg/cm^2. A visual inspection of the interior and exterior painted surfaces was also done to rate the condition of the surfaces.

Soil Measurements

Three core soil samples were taken on each side of the house around the perimeter of the foundation where bare soil was present (a maximum of 12 core samples) and were combined for a composite foundation sample. Core samples (8 to 10) were also taken from the principal outside play area, when a bare surface was present. All core samples were taken at a depth of ½ inch.

Soil samples were thoroughly mixed and sieved into coarse and fine fractions using a 2 mm mesh sieve followed by a 250 *u*m mesh sieve, respectively. Each fraction was analyzed separately. Digestion was completed using EPA method SW846-3050, followed by flame atomic absorption spectroscopy analysis using EPA method 239.1. The detection limit for lead in soil samples was 10 µg/g. Blank samples were inserted at the same frequency as for dust samples.

Water Measurements

Two water samples were taken for each child enrolled; all homes use city water. In contrast with all other environmental samples, water samples were collected by the respondent or parent. Parents were instructed to collect the specimens after the water had not been used for at least 8-hours. One sample was a first-draw sample and the second sample was collected after a one-minute flush. For both samples, the parent was instructed to collect the sample from the cold water faucet in the kitchen, with the faucet turned on at a moderate flow rate.

Drinking water was analyzed for lead using EPA method 200.9. One field blank was inserted into the sample stream once each day. One instrument duplicate blank and one deionized water blank were analyzed for every 10 samples.

Data Management

A Lead Prevention Trial Office was established to provide for the quality control of data and the appropriate analyses of these data. This Office was a collaborative effort of the Department of Pediatrics and the Department of Biostatistics at The University of Rochester School of Medicine and Dentistry. Key positions in this Office were: the Project Director, an analyst/programmer, the investigators, and the biostatisticians. Data were entered and verified by Rochester Information Management Center and the Strong Memorial Hospital Information System.

The data checking system consisted of three stages. During stage 1, data sent on forms from the field to the Lead Prevention Trial Office were coded and visually checked for missing, unclear or inconsistent data by the Project Director. Queries were sent by the Project Director to the fieldworker for clarification. Incomplete and incorrect forms were returned for verification and data correction. Data forms passing the stage 1 validation were sent to Rochester Information Management Center and to the Strong Memorial Hospital Information System for data entry (stage 2). Data were transmitted to Biostatistics by e-mail. The analyst/programmer then ran programs to further check the data for continuous variable range errors, missing data, logical checks, and date errors. The error reports and data listings were produced for the Project Director to review. Finally, during stage 3, data that had passed the first and second stages of data validation were added to the master database on the VAX station 4000 by the programmer. Reports of all errors found during these stages of data verification and validation were sent to the Project Director.

A SAS database was created by the analyst/programmer for the data to be entered/transferred on the VAX station 4000. Listings were prepared for visual checking against the codesheets. In addition, range and logic checks were performed. The Project Director checked these listings and prepared lists of questions for the fieldworkers. Interviewers or environmental technicians with overdue or problematic forms were identified and contacted. The study data were stored and analyzed on a VMS system which has built-in security in the operating system.

Statistical Analyses

Descriptive statistics were calculated for all variables in order to examine their distributions, to assess the appropriateness of the chosen coding, and to determine whether particular variables should be log transformed. For all statistical analyses, blood lead levels and all environmental lead measurements were log transformed (base 10). All analyses were based on version 1 of the data set, March 24, 1994.

Bivariate Analysis

Scatter plots of $\log_{10}$ blood lead (BPb) versus continuous independent variables were examined to look for linear trends, and Pearson correlation coefficients between log(BPb) and these independent variables were calculated. When the independent variable was categorical, either a t-test or an analysis of variance (ANOVA) was performed to determine whether there were differences in mean log(BPb) between the categories.

Characteristics of children who had blood lead levels < 10 µg/dL versus those children who had a blood lead level ≥ 10 µg/dL were tabulated and compared using t-tests, the Wilcoxon test, chi-square tests, or Fisher's exact test. Characteristics of children within the age groups 12 to 18 months, 18 to 24 months, and 24 to 31 months were tabulated and compared using ANOVA, chi-square tests, or Fisher's exact test.

Three principal indices of a child's exposure to lead-contaminated dust were used: dust collection method measures, dust collection method by surface measures, and dust collection method by location measures. Thus, for the purposes of statistical analysis, 5 dust collection method variables, 20 dust collection method-by-surface variables, and 25 dust collection method-by-location variables were created for interior dust measurements.

To create the dust collection method-by-surface variables, the dust measurements were cross-classified by the five methods (BRM loading, DVM loading, wipe loading, BRM concentration, and DVM concentration) and four surface types (carpeted and non-carpeted floors, window sills and window wells), and the average of the log transformed dust lead measurements was calculated for each combination. For each of the five methods, a dust collection method variable was created by averaging the method-by-surface variables for that method. To ensure reasonable comparability of this overall lead exposure index from house to house, a method variable was created only if there were dust lead measurements from at least three surface types, including window wells, for a given house. Otherwise, the method variable was treated as missing.

To create the dust collection method-by-location variables, the dust measurements were cross-classified by the five methods (BRM loading, DVM loading, wipe loading, BRM concentration, and DVM concentration) and five locations (play area, child's bedroom, porch, kitchen , and entryway), and the average of the log transformed dust lead measurements was calculated for each combination.

To examine the relative importance of dust collected from different surfaces within the house, the Pearson correlation coefficient between log(BPb) and each of the 20 method-by-surface variables was calculated. Similarly, to examine the relative importance of dust collected from different locations within the house, the Pearson correlation coefficient between log(BPb) and each of the 25 method-by-location variables was calculated.

Multivariate Analyses

A multiple regression model was constructed to address the question of which dust collection method is generally the best predictor of children's blood lead, after adjusting for other factors influencing blood lead. To avoid problems of multiple testing of dust lead variables and overfitting the data, the following procedure was formulated before exploring the dust lead data. All five dust collection measure variables were entered into the initial model along with all possible covariates which were significant ($p < 0.10$) in the bivariate analyses. Among the variables representing potential sources of lead other than dust, one variable each for interior paint, soil, and water (all log transformed) was selected for inclusion in the initial model based on the strength of its correlation with log(BPb).

A backward selection process was used to eliminate non-significant covariates while all five dust collection method variables were forced to remain in the model. The criterion for dropping a variable was $p > .10$ for each variable. The result of this procedure was to arrive at a common set of covariates for the five dust collection method measures. Each of the five method variables was then entered individually into the regression model along with the significant covariates to obtain the percent of variation in log(BPb) explained by that dust collection method measure and the slope of the relationship between the log transformed dust lead levels and the log(BPb), after adjustment for the other variables in the model.

To determine the dust collection method that was most strongly correlated with children's blood lead levels, the differences between the five unadjusted correlations of log blood lead and the dust lead method variables were tested using a method developed by Hotelling.[29] To test whether a given dust collection method explained more variation in children's blood lead levels than other methods, after controlling for confounding variables in the adjusted analyses, Hotelling's t-test also was applied.[29]

To evaluate the relative contribution of each surface type, each one was entered separately into a model containing the significant covariates as obtained above. To determine which surface should be measured for each method, the common covariates obtained above were forced into a model, and the four surface variables were then allowed to enter the model through a forward selection process.

Variation Explained by All Known Sources of Lead

A measurement for each potential source of lead ascertained (soil, interior paint, and water) was forced into the regression models for wipe loading and BRM loading (regardless of its statistical significance), along with the set of other significant covariates. The percent of variation in log(BPb) explained in the model by each of the known sources, including dust lead, was calculated.

Assessment of Effect Modifiers

Age, handwashing behavior, thumb or finger sucking, serum ferritin level, race, condition of flooring, time spent away from home, and frequency of cleaning were identified *a priori* as possible effect modifiers of the relationship between blood lead and dust lead. (Type of flooring was also recognized as a potential effect modifier and is examined in the method-by-surface analyses.) To assess each potential effect modifier, the variable for the effect modifier along with its interaction term with the dust collection method variable were entered into the regression model from the previous step. All known sources of lead were forced into the models, and the interactions were entered and tested separately.

Logistic Regression

Logistic regression was used to model the relationship between various cut-off values for hypothetical dust lead standards and the proportion of children who have a blood lead level greater than or equal to 10 µg/dL, adjusting for significant covariates. For each of the two "best" dust collection method, a backward selection process was used to select variables for a logistic regression model, with the four method-by-surface variables forced into the model during the selection steps. The same possible covariates as were used in the multiple regression selection process were included in each of these model selection processes.

For each method and surface type, an adjusted estimate of the probability of a blood lead level exceeding or equaling 10 µg/dL was obtained by averaging the logistic regression fitted values for those children in our sample whose dust lead levels did not exceed a specified hypothetical cut-off value. The process was repeated for each possible dust lead value.

RESULTS

Population Characteristics

Of the 5359 children included in the sampling frame, 1536 (29%) families were contacted and interviewed; of those, 376 (25%) were eligible. Of families with children who were eligible, 215 (57%) agreed to participate. Reasons for not participating included: not able to keep appointments (39); not interested (31); no reason given (21); not interested due to blood test (15); moving (14); not worried about lead (14); already had blood lead test (13); too much time involved (10); afraid of landlord (2); and for other reasons (2).

Of the 215 children enrolled between August 29, 1993 and November 20, 1993, 10 (4.7%) were determined to be ineligible after enrollment and were excluded from the analysis (Table 1). Thus, 205 children and families who live in the city of Rochester are included in the analysis (Table 2). A geographic distribution of children who participated in the Lead-In-Dust Study is shown (Figure 1).

Table 1: Reasons for Exclusion of Children After Enrollment

Reason	***No. of Children***
"Major" Renovation Identified	3
Inadequate Blood Sample	2
Not in Random Sampling Frame	2
Inadequate Environmental Sampling	1
Lived Outside of City Limits	1
Same Address but Changed Apartments	1
Total	10

The geometric mean blood lead level for children was 7.7 µg/dL (SD ± 5.1). Forty-eight (23%) of the 205 children had a blood lead level ≥ 10 µg/dL. Of these, 16 (8%) had a blood lead level ≥ 15 µg/dL and 6 (3%) had a blood lead level ≥ 20 µg/dL. The maximum blood lead level was 31.7 µg/dL. There were no significant differences in blood lead levels across the 3 age groups or by gender.

Blood samples were obtained from children at the time of the environmental sampling in 170 (83%) of cases. The remaining 35 (17%) were obtained a median of 8 days after the home visit. None of the 3 children who had blood samples obtained 30 days after the environmental sampling was an outlier for blood lead or dust lead levels, and no data were excluded.

Of the 205 children in the study, 90 (44%) were between the ages of 12 to 18 months; 57 (28%) were between the ages of 18 to 24 months; and 58 (28%) were between the ages 24 and 31 months (Table 2). Forty-two percent of the respondents described their child's racial or ethnic background as Black, 42% as White, 8% as Hispanic or Puerto Rican, and 8% as other. Half (51%) of the children enrolled were girls.

Table 2: Characteristics of Children Enrolled in Lead-In-Dust Study

Characteristic	***Number (percent of total)***
Overall Total	205 (100%)
Blood Lead Level μg/dL (Mean ± SD)	7.7 ± 5.1
Ferritin Level ng/dL (Mean ± SD)	27.6 ± 15.4
Age	
12-18 months	90 (44%)
18-24 months	57 (28%)
24-30 months	58 (28%)
Race	
Black	86 (42%)
White	86 (42%)
Hispanic/Puerto Rican	16 (8%)
Other	17 (8%)
Sex	
Male	101 (49%)
Female	104 (51%)
Months Lived at Address (Mean ± SD)	19.6 ± 5.4
Vitamin Use	
Yes	38 (19%)
No	165 (81%)
Ever Breast Fed	
Yes	91 (44%)
No	114 (56%)
History of Anemia	
Yes	35 (17%)
No	167 (83%)

Behaviors of children that would potentially increase their exposure to lead in their environments are shown (Table 3). Thirty-one percent of children sucked their thumb or fingers; 54 (27%) of children had been observed to eat soil; and 20 (10%) had put paint chips in their mouth. On average, children were reported to spend approximately 5.1 hours away from their home each week (Table 4).

Table 3: Behaviors of Lead-In-Dust Study Children

Characteristic	***Number (percent of total)***
Uses Pacifier	
Yes	32 (16%)
Never/Rarely	173 (84%)
Sucks Thumb/Finger	
Yes	63 (31%)
Never/Rarely	142 (69%)
Uses Bottle	
Yes	105 (51%)
Never/Rarely	100 (49%)
Puts Mouth on Window Sill	
Yes	52 (25%)
Never/Rarely	153 (75%)
Eats Dirt/Soil	
Yes	54 (27%)
Never/Rarely	149 (73%)
Puts Paint Chips in Mouth	
Yes	20 (10%)
Never	185 (90%)
Hands Always Washed After Play/Before Eating	
Yes	53 (26%)
No	152 (74%)

Table 4: Activities of Lead-In-Dust Study Children

Characteristic	***Number (percent)***
Age (months) Began to Crawl (Mean ± SD)	7.2 ± 1.8
Hours Spent Outdoors/Week (Mean ± SD)	16.5 ± 15.9
Plays in Grass	147 (74%)
Plays on Concrete	156 (78%)
Plays in Bare Soil	111 (56%)
Plays in Sandbox	41 (22%)
Plays on Porch	130 (66%)
Plays in Other Areas	35 (21%)

Hours Spent Away From Home/Week (Mean ± SD)	5.1 ± 6.4
Spends Time at Daycare	12 (6%)
Spends Time at Nursery	8 (4%)
Spends Time at Sitters	14 (7%)
Spends Time at Relatives	89 (45%)

One hundred and seven (55%) of families reported an annual income of less than $15,500; 90 (44%) of families were currently married; and 131 (64%) rented their home (Table 5). One hundred and one families (49%) reported at least one smoker in their household, and 122 (60%) of parents had a high school education or less.

Table 5: Family and Household Characteristics of Lead-In-Dust Study Participants

Characteristic	***Number (percent)***
Marital Status	
Married	90 (44%)
Single	80 (39%)
Single, Living Together	17 (8%)
Divorced, Separated or Widowed	17 (8%)
Income Below $15,500	107 (55%)
Rents Housing	131 (64%)
High School Education or Less	122 (60%)
Interior Renovation Since Living There	64 (31%)
Exterior Renovation Since Living There	57 (28%)
Frequency of Cleaning	
Vacuums Every Week	136 (66%)
Wet Mops Every Week	158 (77%)
Sweeps Every Week	182 (89%)
Cleans Window Sills and Wells Every Week	15 (7%)
Smoker in Household	101 (49%)
Eats From Pottery Dishes	18 (9%)
Stores Food in Cans	34 (17%)
House Built Before 1950	126 (62%)
Floors in Poor Condition	17 (9%)

There were no significant differences in these behaviors and activities across the three age groups with the exception of reported ingestion of soil and number of hours played outdoors (Table 6). Compared to other children, those who were 18 to 24 months of age were more likely to be reported as having put soil or dirt in their mouths ($p = 0.03$), and the number of hours that children reportedly spent outdoors during the summer months increased with age ($p = .01$). There were more children in the younger age group (12 to 18 months of age) whose families had a reported income below $15,500.

Table 6: Characteristics of Children in the Lead-In-Dust Study by Age Group*

	12-18 Months	*18-24 Months*	*24-30 Months*	
Characteristic	***n= 90***	***n= 57***	***n= 58***	***p-value***
Age (Mean ± SD)	15.3 ± 1.6	21.3 ± 1.6	27.3 ± 1.6	-
Blood Lead µg/dL (Mean ± SD)	7.7 ± 4.9	7.1 ± 5.2	8.4 ± 5.4	NS
Ferritin Level ng/dL (Mean ± SD)	27.8 ± 15.0	23.7 ± 16.7	31.1 ± 14.1	.003
Age (mos.) Began to Crawl (Mean ± SD)	7.2 ± 2.1	7.1 ± 1.5	7.2 ± 1.6	NS
Hours Play Outdoors (Mean ± SD)	13.8 ± 15.7	15.3 ± 15.0	21.9 ± 16.1	.01
Hours Away From House/Week (Mean ± SD)	4.6 ± 6.1	5.0 ± 6.4	5.9 ± 6.9	NS
	No. (%)	*No. (%)*	*No. (%)*	
	n = 90	***n = 57***	***n = 58***	***p-value***
Sucks Thumb or Finger	25 (28%)	18 (32%)	20 (34%)	NS
Puts Paint Chips in Mouth	10 (11%)	5 (9%)	5 (9%)	NS
Puts Mouth on Window Sill	20 (22%)	18 (32%)	14 (24%)	NS
Eats Soil/Dirt	18 (20%)	22 (40%)	14 (24%)	.03
Hands Always Washed	19 (21%)	14 (25%)	20 (34%)	NS
Plays Often on Floor	82 (91%)	54 (95%)	51 (88%)	NS
Race				NS
Black	42 (47%)	19 (33%)	25 (43%)	
White	31 (34%)	28 (49%)	27 (47%)	
Hispanic/Puerto Rican	8 (9%)	6 (11%)	2 (3%)	
Other	9 (10%)	4 (7%)	4 (7%)	
Lives in Rental Property	62 (69%)	36 (63%)	33 (57%)	NS
Income Less Than $15,500	55 (65%)	27 (49%)	25 (45%)	.03

* Test of no difference across age group

Environmental Lead Measurements

The geometric mean dust lead levels using the 5 different dust collection methods by surface type and location are shown (Tables 7 and 8, respectively). The BRM, a vacuum method which has a high flow rate, appears to be more efficient at picking up lead-contaminated dust than either the DVM or the Wipe Method, and the Wipe Method appears to be more efficient at picking up lead-contaminated dust compared with the DVM. These findings were consistent for carpeted floors, window sills and window wells, but the Wipe Method appeared to be more efficient at picking up lead-contaminated dust from non-carpeted floors. Thus, in general, the BRM collected dust with higher lead loading than both the Wipe Method (except for non-carpeted floors) and the DVM, and collected a higher concentration of dust lead than the DVM. For all three dust collection methods, lead loading and concentration were highest in the window wells, lower on the interior window sills, and lowest on the floors.

Table 7: Geometric Mean Dust Lead Measurements (± 2 SD) for Each Dust Collection Method Measure by Surface Type*

	Window Sill	Window Well	Non-carpeted Floors	Carpeted Floors
BRM Loading	232 [4, 14922]	11874 [26, 5365819]	11 [0, 343]	187 [10, 3395]
BRM Concentration	2652 [61, 115373]	6114 [65, 579533]	528 [25, 11029]	242 [31, 1916]
DVM Loading	19 [0, 766]	370 [3, 45177]	1 [0, 27]	3 [0, 62]
DVM Concentration	625 [14, 27035]	1709 [17, 171081]	231 [7, 7556]	226 [24, 2135]
Wipe Loading	166 [12, 2266]	2759 [29, 264752]	16 [2, 140]	11 [2, 75]

*$\bar{X}$, $\bar{X}$ -2 SD, $\bar{X}$ +2 SD were calculated on the Log_{10} scale and then exponentiated to convert to raw scale.

Table 8: Geometric Mean Dust Lead Measurements (± 2 SD) for Each Dust Collection Method Measure by Location of Dust Sampling*

	Play Area	Child's Bedroom	Porch	Kitchen	Entryway
BRM Loading	371 [7, 18698]	443 [5, 42113]	548 [7, 43370]	74 [0, 15834]	88 [0, 15881]
BRM Concentration	1078 [43, 27216]	1357 [49, 37835]	1132 [42, 30150]	1118 [22, 56260]	468 [19, 11243]
DVM Loading	16 [0, 657]	16 [0, 734]	17 [1, 446]	4 [0, 473]	3 [0, 124]
DVM Concentration	555 [23, 13505]	523 [19, 14730]	557 [52, 6017]	372 [5, 29573]	329 [18, 5967]
Wipe Loading	106 [5, 2345]	111 [4, 3297]	57 [4, 871]	63 [2, 2574]	18 [2, 215]

*$\bar{X}$, $\bar{X}$ -2 SD, $\bar{X}$ +2 SD were calculated on the Log_{10} scale and then exponentiated to convert to raw scale.

We calculated the number and percent of housing units in the Lead-In-Dust Study that exceeded the current post-abatement clearance standards and EPA guidance levels for the wipe method. Six (3%) of houses had non-carpeted floors which exceeded the 100 µg/ft² EPA guidance level, and 4 (2%) exceeded the the 200 µg/ft² HUD post-abatement clearance standard. In contrast, 34 (17%) of houses had interior window sills that exceeded post-abatement clearance standard and 129 (68%) of houses had window wells that exceeded the current post-abatement clearance standard (Table 9).

Table 9: Wipe Lead Loading Values Exceeding Current Post-Abatement Clearance Standards and EPA Guidance Levels on Three Surfaces

Surface Type	***Lead Loading (μg/ft²)***	***No.***	***Percent***
Non-Carpeted Floors	< 100	191	97
	≥ 100	6	3
Non-Carpeted Floors	< 200	193	98
	≥ 200	4	2
Window Sills	< 500	164	83
	≥ 500	34	17
Window Wells	< 800	61	32
	≥ 800	129	68

The geometric mean lead measurements of water, soil, paint, and exterior dust are shown (Table 10). Foundation soil lead levels appeared to be higher than play area soil lead levels and coarse-sieved foundation soil fraction appeared to have a higher lead concentration than fine-sieved soil fraction. Water lead levels were generally low, with the highest value at 157 μg/L.

Table 10: Geometric Mean Lead Levels of Environmental Samples in the Lead-In-Dust Study

Type and Location of Sample	*no.*	*Geometric Mean*	*± 2 SD*
First Flush Water (μg/L)	203	.0012	[.0001, .0122]
1-Minute Water (μg/L)	202	.0009	[.0001, .0074]
Coarse Foundation Soil (μg/kg)	182	981	[52, 18565]
Fine Foundation Soil (μg/kg)	182	732	[54, 9994]
Coarse Play Area Soil (μg/kg)	82	299	[30, 2961]
Fine Play Area Soil (μg/kg)	82	271	[35, 2104]
XRF Interior			
Median (mg/cm²)	205	1	[0, 8]
Maximum (mg/cm²)	205	12	[1,188]
XRF Exterior (mg/cm²)	88	7	[0, 125]
External Dust			
DVM Loading (μg/ft²)	150	18	[1, 576]
BRM Loading (μg/ft²)	145	335	[7, 17271]

$\bar{X}$, $\bar{X}$-2SD, $\bar{X}$ + 2SD were calculated on the Log_{10} scale and then exponentiated to convert to raw scale.

Bivariate Analyses

Children who were reported to put soil or dirt in their mouths and those who reportedly put paint chips in their mouths were significantly more likely to have a blood lead level greater than 10 µg/dL compared to children who were not reported to have these behaviors (Table 11). Contrary to what we anticipated, thumb or finger sucking was not associated with a child having a blood lead level higher than 10 µg/dL and children who were reported to wash their hands frequently were more likely to have a blood lead level ≥ 10 µg/dL. Black children were significantly more likely to have elevated blood lead levels.

Table 11: Characteristics of Children in the Lead-In-Dust Study by Children's Blood Lead Levels

Characteristic	***< 10 µg/dL n = 157***	***≥ 10 µg/dL n = 48***	***p-value***
Blood Lead µg/dL (Mean ± SD)	5.5 ± 2.2	15.1 ± 5.0	-
Ferritin Level ng/dL (Mean ± SD)	26.7 ± 15.3	30.4 ± 15.7	.07*
Age (Mean ± SD)	20.3 ± 5.2	20.7 ± 5.5	NS
Age (months) Began to Crawl (Mean ± SD)	7.2 ± 1.8	7.1 ± 1.7	NS
Hours Play Outdoors (Mean ± SD)	15.6 ± 14.9	19.4 ± 18.9	NS
Hours Away From House/Week (Mean ± SD)	5.0 ± 6.3	5.3 ± 6.7	NS
	No. (%)	***No. (%)***	***p-value***
Race			<.001
Black	53 (34%)	33 (69%)	
White	80 (51%)	6 (13%)	
Hispanic/Puerto Rican	12 (8%)	4 (8%)	
Other Ethnic or Racial Group	12 (8%)	5 (10%)	
Sucks Thumb or Finger	51 (32%)	12 (25%)	NS
Puts Paint Chips in Mouth	11 (7%)	9 (19%)	.02
Puts Mouth on Window Sill	35 (22%)	17 (35%)	.07
Eats Soil/Dirt	37 (24%)	17 (36%)	.09
Hands Always Washed	35 (22%)	18 (38%)	.04
Plays Often on Floor	144 (92%)	43 (90%)	NS

* Non-parametric test NS = Not Significant

Household and family characteristics that were significantly associated with a child having a blood lead level higher than 10 µg/dL included living in rental property, single parent household, a parent with a high school education or less, and having an income less than $15,500, (Table 12).

Table 12: Family and Household Characteristics of Children by Children's Blood Lead Levels

Characteristic	***<10 µg/dL n = 157 No. (%)***	***≥ 10 µg/dL n = 48 No. (%)***	***p-value***
Lives in Rental Property	87 (55%)	44 (92%)	<.001
Single Parent Household	63 (40%)	34 (71%)	<.001
Parent with High School Education or Less	81 (52%)	41 (85%)	<.001
Income Less than $15,500	72 (48%)	35 (78%)	<.001

Dust lead loading and dust lead concentration are, in general, significantly correlated with blood lead levels for all four surface types (Table 13). However, DVM dust lead loading, DVM dust lead concentration, and BRM dust lead concentration for non-carpeted floors were not significantly correlated with children's blood lead levels. Plots of log BPb versus average log dust lead loading on non-carpeted floors using the BRM and the Wipe Method (Figures 2 and 3, respectively), and for blood lead versus geometric mean of dust lead loading on non-carpeted floors are shown (Figures 4 and 5, respectively).

Table 13: Correlations of Logs of Children's Blood Lead and Logs of Dust Lead Levels Using 5 Dust Collection Method Measures by Surface Type (Sample Size in Parentheses)

Dust Collection Method Measure	**Window Sill**	**Window Well**	**Non-carpeted Floors**	**Carpeted Floors**
BRM Loading	.34** (199)	.35** (190)	.35** (194)	.36** (179)
BRM Concentration	.19** (195)	.23** (188)	.10 (192)	.25** (178)
DVM Loading	.23** (200)	.31** (191)	.14 (198)	.27** (181)
DVM Concentration	.25** (193)	.23** (190)	.01 (182)	.18* (177)
Wipe Loading	.34** (198)	.29** (190)	.32** (197)	.26** (179)

* p<.05 ** p<.01

Dust lead levels and children's blood lead levels are also highly correlated for most of the locations that were sampled (Table 14). Dust lead loading measured with the wipe method was significantly correlated with children's blood lead levels for all of the locations sampled, including the porch floor and entryway floor. BRM dust lead loading and DVM dust lead loading were significantly correlated with children's blood lead levels for four of the five locations.

Table 14: Correlations of Logs of Children's Blood Lead and Logs of Dust Lead Levels Using 5 Dust Collection Method Measures by Location of Dust Sampling (Sample Size in Parentheses)

Dust Collection Method Measures	Play Area	Child's Bedroom	Porch	Kitchen	Entryway
BRM Loading	.28** (199)	.41** (198)	.04 (124)	.23** (203)	.15* (178)
BRM Concentration	.16* (199)	.33** (197)	.03 (122)	.11 (199)	.08 (174)
DVM Loading	.23** (199)	.29** (201)	.22* (125)	.16* (202)	.11 (181)
DVM Concentration	.19** (197)	.24** (200)	.13 (123)	.07 (193)	.01 (172)
Wipe Loading	.31** (196)	.27** (201)	.28** (125)	.27** (205)	.29** (180)

* $p< .05$ ** $p< .01$

Correlations of Dust Lead Loading and Dust Lead Concentration

Correlations of blood lead with dust lead levels averaged across all surfaces of children's homes were significant for all five dust collection methods (Table 15). However, for each of the two vacuum methods, dust lead loading had a significantly higher correlation with children's blood lead levels than does dust lead concentration ($p < 0.0001$ for the BRM and $p = .04$ for DVM). Lead loading measurements obtained using the BRM and the wipe methods were more highly correlated with children's blood lead levels than those obtained using the DVM ($r = .46$, .39, and .32 respectively), but the correlations for the BRM and the wipe method were not significantly different from each other ($p = .12$). Correlations for dust lead loading obtained using the BRM and DVM were significantly different from each other ($p =.01$), whereas correlations for wipe lead loading and the DVM lead loading were not significantly different ($p = .16$).

Table 15: Correlations of Logs of Dust Lead Levels and Logs of Blood Lead Levels by Dust Collection Method Measures

Method	***Pearson Correlation Coefficient***	***95% CI***	***p value***
BRM ($\mu g/ft^2$)	0.46	.35, .58	.0001
Wipe ($\mu g/ft^2$)	0.39	.27, .51	.0001
BRM ($\mu g/g$)	0.27	.14, .41	.0002
DVM ($\mu g/ft^2$)	0.32	.19, .45	.0001
DVM ($\mu g/g$)	0.23	.10, .37	.0013

* Slopes are based on regression of log of blood lead on averaged logs of dust lead ($\mu g/ft^2$ or $\mu g/g$)

Other Environmental Sources of Lead

The geometric mean lead concentration of soil was significantly associated with children's blood lead levels (Table 16). The correlation coefficient for the total soil fraction and the fine soil fraction were similar, as were the correlations of children's blood lead levels and foundation soil compared with play area soil.

Table 16: Correlations of Logs of Children's Blood Lead Levels with Logs of Lead Variables

Variable	no.	Correlation Coefficient
Water		
First Flush	203	-.01
1 Minute Flush	202	.05
Soil		
Coarse Foundation	182	.38**
Fine Foundation	182	.35**
Coarse Play Area	82	.34**
Fine Play Area	82	.32**
Interior Paint		
Maximum	205	.15*
Median	205	.09
Exterior Paint	88	.09
Exterior Dust		
DVM ($\mu g/ft^2$)	150	.34**
DVM ($\mu g/g$)	147	.21*
BRM ($\mu g/ft^2$)	145	.18*
BRM ($\mu g/g$)	143	.17*

* $p < .05$ ** $p < .01$

The maximum concentration of interior paint lead was significantly correlated with children's blood lead levels, but median lead concentration of interior paint and exterior paint lead levels were not correlated with children's blood lead levels. Water lead levels also were not significantly correlated with children's blood lead levels (Table 16).

With the exception of water lead and exterior paint values, and exterior dust for BRM dust lead loading, other environmental lead measurements, including dust lead levels measured using both the wipe method and the BRM sampler, were generally significantly correlated with each other (Table 17 and Table 18).

Table 17: Intercorrelations of Logs of Environmental Lead Measures and BRM Dust Lead Loading

	1-Minute	*Coarse Soil*	*Fine Soil*	*Interior*	*Exterior*	*Exterior*	*Carpeted*	*Non-Carpeted*	*Windowsill*	*Window well*
First Flush Water	.77**	.07	-.01	-.09	-.01	.04	-.10	.12	.05	-.04
1-Minute Water		.07	.01	.05	.05	.03	-.14	.15	.09	-.09
Foundation Coarse Soil			.84**	.52**	.37**	.19	.37**	.31**	.40**	.38**
Foundation Fine Soil				.54**	.34**	.17	.27**	.27**	.40**	.40**
Interior Paint (Max)					.34**	.37**	.29**	.31**	.54**	.61**
Exterior Paint						.26	.12	.19	.25	-.07
Exterior Dust (BRM load)							.28	.18	.27**	.17**
Carpeted Floor (BRM load)								.26**	.31**	.32**
Non-Carpeted Floor (BRM load)									.42**	.22*
Windowsill Dust (BRM load)										.55**

*p< .01 ** p< .001

Table 18: Intercorrelations of Logs of Environmental Lead Measures and Wipe Dust Lead Loading

	1-Minute	*Coarse*	*Fine Soil*	*Interior*	*Exterior*	*Exterior*	*Carpeted*	*Non-Carpeted*	*Windowsill*	*Window well*
First Flush Water	.77**	.07	-.01	-.09	-.01	-.02	-.01	.01	.07	-.06
1-Minute Water		.07	.01	.05	.05	-.01	-.08	-.05	.02	-.14
Foundation Coarse Soil			.84**	.52**	.37**	.40**	.26	.29**	.41**	.37**
Foundation Fine Soil				.54**	.34**	.35**	.19	.30**	.39**	.41**
Interior Paint (Max)					.34*	.37*	.27**	.30**	.50**	.57**
Exterior Paint						.25	.15	.04	.15	.07
Exterior Dust (BRM load)							.41**	.35**	.33**	.27
Carpeted Floor (BRM load)								.50**	.45**	.31**
Non-Carpeted Floor (BRM load)									.43**	.34*
Windowsill Dust (BRM load)										.60**

*p< .01 ** p< .001

Multivariate Analyses

In a backward selection multiple regression model, we found that, in addition to dust lead loading, Black race, children putting soil in their mouths, single parent household, and having a higher ferritin level were all significantly associated with higher blood lead levels among children. Variables included in the selection process are shown (Table 19).

Table 19: Multiple Regression of Log of BPb of Children in the Lead-In-Dust Study and Individual Variables

Variable	***Unadjusted Coefficient§***	***Adjusted Coefficient†***	***Coefficient‡***
Ferritin Level	.192*	.148	.138*
Puts Paint Chips in Mouth	.174**	.044	
Puts Mouth on Windowsill	.105*	.006	
Eats Dirt/Soil	.074	.121*	.111**
Hands Always Washed	.096*	.018	
Floor in Poor Condition	.209**	.067	
Mean Hours Played Outside/Week	.002*	.001	
Interior Renovation Done	-.097	-.019	
Exterior Renovation Done	-.085*	-.028	
Black Race	.240**	.115	.153**
Hispanic/Puerto Rican	-.036	.023	
Other Race (Non-White)	-.002	.065	
Income > $15,500	-.197**	-.010	
Owner Occupied Home	-.188**	.007	
Parent Has Some College Education	-.203**	-.033	
Single Parent Household	.189**	.063	.077
Water Lead	.028	.068	
Interior Paint Lead	.214	.283	
Interior Paint Quality	.006	.127	
Interior Paint Quality *Lead	-.063	-.118	
Soil Lead (if soil present)	.159**	.043	
Frequency of Cleaning	-.085**	-.001	
Ever Breast Fed	-.099**	-.012	
Vitamins Used	-.110*	.006	
Smoker in Household	.091	.041	
Eats on Pottery Dishes	-.159*	-.048	

* p value < .05
** p value < .01

§ Coefficients from simple linear regression model
† Coefficients from multivariate regression model
‡ Coefficients with p value < 0.10 for final model
ƒ Ferritin levels and environmental lead variables were log transformed

The incremental change in log of blood lead levels estimated to be associated with changes in log dust lead levels, after controlling for the other significant predictors, is shown for each of the 5 dust collection methods (Table 20). Dust lead loading using the BRM accounted for the largest amount of variation in children's blood lead levels (13.7%) compared with all other dust collection method measures. The wipe method also a highly significant predictor of children's blood lead levels, explaining 10.1% of the variation, whereas DVM loading and both measures of concentration explained lower amounts of the variation in children's blood lead levels.

Table 20: Adjusted Slopes and Percent Variation in log Blood Lead Accounted for by Dust Collection Method Measures

Method	*Slope **	*95% CI*	*p value*	*Percent Variation Accounted for by DCM*
BRM (μg/ft²)	.151	.103, .200	.0001	13.7
Wipe (μg/ft²)	.176	.108, .243	.0001	10.1
DVM (μg/ft²)	.119	.058, .181	.0002	5.9
BRM (μg/g)	.138	.075, .200	.0001	7.5
DVM (μg/g)	.096	.027, .164	.007	3.2

* Slopes are based on regression of log of blood lead on averaged logs of dust lead (μg/ft² or μg/g)

The difference between the partial correlations for BRM lead loading and wipe lead loading was not significant (p = .16), but the partial correlation for BRM lead loading was significantly different than that for both BRM lead concentration and DVM lead loading (p = .001 and p = .004, respectively). The partial correlation of wipe lead loading was not significantly different from those for DVM lead loading or BRM lead concentration (p = .11 and p = .36, respectively). Finally, in contrast with the unadjusted comparison, the partial correlation for DVM lead loading was not significantly different than that for DVM lead concentration.

Complete models for BRM and Wipe loading are shown (Tables 21 and 22). For both models, dust lead loading and Black race were the variables which explained the majority of the variation in children's blood lead levels. Adjusted models for each of the four surface types are shown (Table 23 and 24).

Table 21: Percent Variation Explained by Variables in Dust Collection Model Using BRM Loading

Covariate	***Slope****	***95% CI***	***p value***	***Percent Variation Accounted for***
BRM Lead ($\mu g/ft^2$)	.15	(.10, .20)	.0001	13.7
Black Race	.17	(.09, .25)	.0001	6.5
Eats Dirt/Soil	.11	(.04, .19)	.003	3.3
Single Parent Household	.09	(.01, .17)	.02	2.0
Ferritin	.12	(-.02, .26)	.07	1.2

* Slopes are based on the regression of log of blood lead on averaged logs of dust lead ($\mu g/ft^2$). Ferritin levels also were log transformed.

Table 22: Percent Variation Explained by Variables in Dust Collection Model Using Wipe Method

Covariate	***Slope****	***95% CI***	***p value***	***Percent Variation Accounted for***
Wipe ($\mu g/ft^2$)	.18	(.11, .24)	.0001	10.1
Black Race	.16	(.08, .24)	.0001	6.1
Eats Dirt/Soil	.13	(.06, .21)	.0009	4.5
Single Parent Household	.10	(.02, .18)	.013	2.4
Ferritin	.12	(-.02, .26)	.10	1.1

* Slopes are based on the regression of log of blood lead on averaged logs of dust lead ($\mu g/ft^2$). Ferritin levels also were log transformed.

Table 23: Adjusted Slopes for Wipe Method by Surface Type

Surface Types	***Slope ****	***95% CI***	***p value***	***Percent Variation Accounted for***
Non-Carpeted Floor	.14	(.07, .20)	.0001	5.7
Carpeted Floor	.12	(.04, .20)	.004	3.6
Window Sill	.14	(.08, .19)	.0001	8.2
Window Well	.07	(.04, .10)	.0001	6.1

* Slopes are based on regression of log of blood lead on averaged logs of dust lead loading ($\mu g/ft^2$).

Table 24: Adjusted Slopes for BRM Loading By Surface Type

Surface Types	***Slope ****	***95% CI***	***p value***	***Percent Variation Accounted for***
Non-Carpeted Floor	.11	(.07, .16)	.0001	9.5
Carpeted Floor	.10	(.05, .16)	.0004	5.5
Window Sill	.08	(.05, .12)	.0001	7.3
Window Well	.06	(.04, .09)	.0001	9.2

* Slopes are based on regression of log of blood lead on averaged logs of dust lead loading ($\mu g/ft^2$).

To determine which surface(s) should routinely be measured, regression analyses for BRM loading by surface (i.e., carpeted and non-carpeted floors, interior window sills and window wells) and for wipe loading by surface were done adjusting for other significant predictors. For the BRM, non-carpeted floors and window wells were significantly associated with children's blood lead levels, whereas for the wipe, non-carpeted floors and interior window sills were significantly associated with children's blood lead. These results hold true even when only those children who had 2 or more carpeted floors were analyzed.

To determine whether the BRM, the wipe method, or a combination of the two dust collection methods should be used, the above four surface variables were entered into a regression model. Thus, 2 BRM by surface measurements (non-carpeted floors and window wells) and 2 wipe by surface measurements (non-carpeted floors and interior window sills) were entered into the model, along with the significant covariates. When dust lead loading measurements using the BRM on window wells and on non-carpeted floors were included in the model, neither dust lead loading as measured by the wipe method on non-carpeted floors or on interior window sills made an additional significant contribution.

A measurement for each potential source of lead ascertained (soil, interior paint, and water) was forced into the regression model obtained above (regardless of its statistical significance). The BRM and the wipe method were used in separate analyses as the dust-lead measurement variable. The percent of variation in log(BPb) explained in the model by all known sources was calculated, along with the percent contribution of dust lead among all known sources (Table 25).

Table 25: Dust Collection Models Including Other Environmental Sources of Lead

Dust Measured Using BRM Method				
Covariate	***Slope****	***95% CI***	***p value***	***% Variation Accounted for***
BRM ($\mu g/ft^2$)	.19	(.12, .25)	.0001	11.1
Lead in Coarse Soil	.06	(-.003, .12)	.06	1.2
Soil Present	-.15	(-.35, .06)	.160	.7
Water Lead	.05	(-.01, .12)	.120	.8
Interior Paint Lead	-.10	(-.17, -.02)	.02	2.0
Ferritin	.13	(.003, .26)	.047	1.3
Eats Dirt/Soil	.09	(.02, .16)	.013	2.1
Black Race	.13	(.05, .21)	.001	3.7
Single Parent	.08	(.01, .15)	.023	1.7
Dust Measured Using Wipe Method				
Wipe ($\mu g/ft^2$)	.20	(.12, .28)	.0001	8.1
Lead in Coarse Soil	.08	(.02, .14)	.01	2.1
Soil Present	-.21	(-.42, -.006)	.045	1.4
Water Lead	.07	(.001, .13)	.048	1.4
Interior Paint Lead	-.06	(-.13, .01)	.10	0.9
Ferritin	.10	(-.03, .23)	.13	0.8
Eats Dirt/Soil	.10	(.03, .17)	.006	2.7
Black Race	.14	(.06, .22)	.0005	4.3
Single Parent	.08	(.01, .15)	.025	1.8

* Slopes are based on the regression of log of blood lead on averaged logs of dust lead ($\mu g/ft^2$). Soil lead, water lead, paint lead, and ferritin levels also were log transformed.

We also assessed the effect of potential modifiers on the relationship of blood lead levels and dust lead. There was a significant interaction of dust lead by condition of flooring, but only for the wipe method. None of the other effect modifiers, including age, handwashing, race, ferritin levels, type and frequency of cleaning, and time spent away from home were significant.

Logistic Regression

In the logistic regression model to predict the probability of a blood lead level greater than or equal to 10 µg/dL, eating dirt or soil, and whether the respondent rented versus owned the home, were the significant covariates, in addition to dust lead loading measured using the BRM method (Table 26). For the wipe method, the significant covariates, in addition to dust lead loading, were eating soil or dirt, soil lead levels, and the respondent's level of education. The two models for dust lead from non-carpeted floors are shown (Table 26).

Table 26: Logistic Regression Models to Predict Blood Lead ≥ 10 μg/dL

Covariate	Estimate†	95% CI	p value
BRM Loading on Non-Carpeted Floors			
Dust Lead (μg/ft²)	1.22	(0.58, 1.86)	.0002
Eats Dirt/Soil	1.21	(0.32, 2.10)	.008
Owns Home	-2.63	(-3.84, -1.42)	.0001
Wipe Loading on Non-Carpeted Floors			
Dust Lead (μg/ft²)	1.81	(0.72, 2.91)	.001
Soil Lead Levels	0.93	(0.14, 1.71)	.02
Soil Present	-3.50	(-6.26, -0.74)	.01
Eats Dirt/Soil	1.11	(0.21, 2.01)	.02
College Education	-1.73	(-2.72, -0.73)	.0007

† Estimates are based on average logs of dust lead loading (μg/ft²). Soil lead values also were log transformed.

Adjusted estimates for the proportion of children with blood lead levels ≥ 10 μg/dL, given a hypothetical dust lead standard, are shown for a range of possible dust lead standards (Figures 6 and 7). The upper left plot shows the predicted proportion of children with blood lead levels ≥ 10 μg/dL, given a dust lead loading level below a hypothetical standard for non-carpeted floors using the BRM method; the dashed lines indicate the 95% confidence bands (pointwise) for this estimate (Figure 6). The upper right plot shows the same estimate, together with a separate estimate for those who own their home versus those who live in rental housing. The lower left plot shows the estimate, together with the distribution of dust lead; this plot serves to illustrate that the estimate for high dust lead loading are less precise due to the scarcity of data at those dust lead levels. The lower right plot shows the estimated proportion of children with a blood lead levels ≥ 10 μg/dL , given a dust lead level below a hypothetical standard for *carpeted* floors. Similar plots for the wipe method are shown (Figure 7), and data are tabulated at specific cut-off values to illustrate the percent of children estimated to have a blood lead level ≥ 10 μg/dL for all 4 surfaces measured. (Table 27)

Table 27: Proportion of Children with Blood Lead Levels ≥ 10 µg/dL for a Range of Hypothetical Dust Lead Standards Using the Wipe Method

	Floors										
	Carpeted Floors		**Non-Carpeted Floors**			**Interior Window Sill**			**Window Well**		
Dust Lead Standard	***Proportion with BPb ≥ 10***	***95% CI***	***Proportion with BPb ≥ 10***	***95% CI***	***Dust Lead Standard***	***Proportion with BPB ≥ 10***	***95% CI***	***Dust Lead Standard***	***Proportion with BPb ≥ 10***	**95% CI**	
5	.038	(.003, .074)	.043	(.005, .082)	50	.101	(.039, .163)	200	.123	(.050, .195)	
10	.099	(.52, .145)	.102	(.049, .156)	100	.148	(.088, .209)	500	.153	(.084, .223)	
15	.147	(.097, .197)	.135	(.080, .191)	200	.156	(.101, .211)	750	.165	(.096, .234)	
20	.166	(.115, .217)	.149	(.097, .202)	300	.162	(.109, .215)	1,500	.158	(.096, .221)	
25	.175	(.124, .226)	.170	(.120, .221)	400	.180	(.128, .232)	3,000	.172	(.111, .233)	
30	.181	(.130, .232)	.180	(.130, .231)	500	.189	(.137, .214)	5,000	.183	(.125, .240)	
35	.192	(.140, .244)	.189	(.137, .240)	600	.195	(.143, .248)	10,000	.199	(.143, .256)	
40	.198	(.145, .250)	.197	(.146, .249)	700	.201	(.149, .253)	20,000	.204	(.148, .259)	

DISCUSSION

Lead-Contaminated Dust and Children's Blood Lead Levels

The findings of this study demonstrate that lead-contaminated house dust is an important contributor of lead to children who have low to moderate blood lead levels (i.e., blood lead levels < 25 μg/dL) and indicate that the proportion of children who are estimated to have a blood lead level $\geq$ 10 μg/dL dramatically increases at dust lead levels considerably lower than current HUD post-abatement standards and EPA guidelines. These data further indicate the need to consider tying any household dust standard to the method by which dust is collected. Moreover, these data indicate that the slope of the blood lead levels and household dust lead relationship is significantly different for floors, window sills, and window wells using the same dust collection method, as well as varying by dust collection method measure. Thus, it is clear that the development of residential dust lead standards requires both explicit designation of a dust collection method and clear articulation of the surfaces to be measured prior to selecting the level(s) of lead-contaminated house dust that are to be considered dangerous.

Although concentration has traditionally been used for measuring environmental toxicants,[23] the findings of this study suggest that lead loading is a more predictive measure of children's blood lead levels than is dust lead concentration for the range of lead-contaminated dust observed in this study. This finding is similar to that of Davies et al, who found that, in a random sample of 97 children in the U.K., dust lead loading is a better predictor of children's blood lead levels than is dust lead concentration.[30] In other studies, both dust lead concentration and loading were highly correlated with children's blood lead levels.[31] These differences may be due to the fact that dust lead concentration is a good predictor of children's blood lead levels at higher dust lead levels. The results of this present study suggest that dust lead loading is a better indicator of the amount of lead available to a child at lower dust lead levels. Regardless of the reason, these data indicate that lead loading is a significantly better predictor of children's blood lead levels.

The mean household dust lead levels in this study are considerably lower than the current HUD post-abatement clearance standard and the recently released EPA guidance levels, both of which use the wipe method for dust sampling. It is important to note that the neither of these are health-based standards. Nevertheless, they are useful for comparative purposes. In this present study, 3% of houses exceeded the 100 $\mu g/ft^2$ EPA guidance level for floors, 2% of houses exceeded the 200 $\mu g/ft^2$ HUD post-abatement clearance standard for floors, and 34 (17%) of houses exceeded the post-abatement standard (500 $\mu g/ft^2$) for interior window sills. Thus, at levels well below the current HUD post-abatement clearance standards and EPA guidance levels, there was a significant association of children's blood lead levels and dust lead loading on both floors and window sills, yet 23% of the children had a blood lead levels $\geq$ 10 μg/dL. In contrast, 129 (68%) of houses exceeded the current HUD post-abatement clearance standard and EPA guidance levels for window wells (Table 9).

Therefore, this study suggests that current post-abatement standards and EPA guidance levels may be set too high for floors and interior window sills. In contrast, the current HUD post-abatement standard and EPA guidance level for window wells may be too low relative to the other surfaces.

Compared with some earlier studies, the dust lead levels in the current study appear low. Direct comparison of the various studies is difficult due to variation in dust sampling protocols, but it appears that dust lead levels observed in the present study are lower than those found in a study done in Rochester in early 1970.[19] However, they appear to be similar to those observed by Rabinowitz et al.[15] Many of the earlier studies were conducted when the concentration of lead in both motor vehicle emissions and painted surfaces was higher. Thus, it is possible that current dust lead levels are, in fact, lower.

Earlier studies reported a wide range of estimates for the change in blood lead levels associated with an increment in household dust lead concentration, between 1 and 10 µg/dL per 1,000 ppm.[23] Fewer studies have measured lead loading.[15, 19-21, 30] There are several reasons for the wide range in these estimates. First, studies which have measured the relationship of children's blood lead levels and dust lead levels have used various dust collection methods. As demonstrated in the current study, the change in blood lead levels for an incremental change in dust lead loading and dust lead concentration is dependent on the dust collection method used. Second, various groups of children were included in these studies, including those of different age groups and socioeconomic status, and samples were often taken during different seasons.[23] Finally, many studies were conducted among populations where an industrial source was present.[23, 32]

During the past two decades, as the contribution of lead from air, food, and water has decreased, and as the mean blood lead levels of children have declined, it is likely that the relative contribution of lead-contaminated house dust to children's blood lead levels has changed. Many of the earlier reported estimates of the incremental change in blood lead levels associated with household dust lead are unadjusted for the contribution of lead from other potential sources, such as atmospheric lead and dietary lead.[23] Current exposure to these other sources of lead are lower than just one decade ago.[33, 34]

A Side-by-Side Comparison of Dust Collection Method

On the basis of the statistical criteria established *a priori*, this analysis found that the BRM had the highest correlation of log(BPb) versus mean log (Dust Pb) loading and explained a larger amount of the variation in children's blood lead levels than the other dust collection method measures. However, the difference between the partial correlations for BRM lead loading and wipe lead loading was not significant, whereas the partial correlation for BRM lead loading was significantly different than that for both BRM lead concentration and

DVM lead loading. Collectively, these data suggest that either the BRM sampler or the wipe method should be used to sample dust.

Results of analyses to determine which surface(s) should routinely be measured showed that for the BRM, non-carpeted floors and window wells were significantly associated with children's blood lead levels, whereas for the wipe, non-carpeted floors and interior window sills were significantly associated with children's blood lead. When dust lead loading as measured with the BRM from window wells and non-carpeted floors was included in the model, dust lead loading as measured by the wipe method did not make an additional significant contribution, suggesting that it is not beneficial to use both dust collection methods.

Each of the dust collection methods has limitations. Dust lead samples taken in the child's bedroom and the principal play area using the five dust collection methods were generally correlated with children's blood lead levels. However, dust samples taken from the entryway floor and porch floor using the two vacuum methods were less well correlated with children's blood lead levels. These differences could be a result of method by location or method-by-surface interactions, or they could be a result of natural sampling variation over the large number of samples examined.

There are also other, non-statistical criteria to inform the decision of whether to use the BRM or the wipe method for large scale sampling. For example, The wipe method appears to be superior to the BRM for ease of use, cost, portability, and minimal burden to respondent and field workers. Other criteria, such as reliability, should also be considered. An analysis of the variability of the BRM and wipe methods will be presented in Volume III of this final report.

Racial Differences in Blood Lead Levels

In this study, Black children had significantly higher blood lead levels compared to White children, and Black race was an independent predictor of blood lead status. In the National Health and Nutrition Examination Survey (NHANES II), Black children also were found to be at increased risk for having an elevated blood lead levels compared to White children for both urban and rural settings, and at both higher and lower incomes.[35] In this current study, Black children were exposed to dust lead levels that were significantly higher than White children, lived in rental property that was not as well maintained as the homes of the more affluent White children, and were largely impoverished. It is likely that there is confounding of dust lead levels and Black race, and preliminary analyses, which are not presented here, indicate that the racial disparity in urban children's blood lead levels may largely be due to differences in environmental exposures.

Soil Ingestion and Soil Lead

In this present study, we found that 27% of children were reported to put soil or dirt in their mouths. Charney and others also found that soil ingestion was significantly associated with having an elevated blood lead level in a population of children with higher blood lead levels (i.e., > 30 µg/dL).[20] The frequency of this behavior was highest at 18 to 24 months of age, the age at which a number of studies have shown a peak in children's blood lead levels.[4, 31] Moreover, since soil ingestion is likely to be a seasonal phenomena in temperate climates, it may contribute to the seasonal elevation of blood lead levels during the summer months.

In the multivariate and logistic regression models using the wipe method, soil lead levels were significantly associated with children's blood lead levels. Previous studies also have found that soil is an important source of lead for urban children. In a case-control study, Charney et al found that children who had an elevated blood lead were significantly more likely to have higher soil lead levels.[20] Similarly, Rabinowitz et al showed that soil lead levels and blood lead levels were highly correlated.[15] Several studies done near lead smelters also have found significant association between soil lead levels and children's blood lead levels.[23, 32] Recently, Weitzman et al demonstrated that, for children who lived in urban housing units which received residential soil abatement, there was a statistically significant, albeit modest, decline in blood lead levels.[22] Collectively, these studies indicate that lead-contaminated soil is an important source of lead for urban children. However, the extent to which soil contributes through direct ingestion and via its contribution to interior house dust is less clear.

Iron Status

Serum ferritin levels, which are reduced in iron deficiency, were higher in children who had higher blood lead levels in this study. Previous studies have suggested that iron deficiency increases lead absorption, which is in direct contrast with our finding.[36, 37] The difference in mean ferritin levels observed is of questionable clinical relevance as regards to children's iron status and may be a spurious finding. However, this finding should not be too quickly discounted. In one study, for example, adults with hemochromatosis (a condition associated with an abnormally high rate of iron absorption), had significantly higher blood lead levels than controls.[38] Thus, there may be a subgroup of children who have an increased intestinal absorption of metals, such as iron or lead.

Household and Family Characteristics

The type of housing (rental versus owner occupied) in this study was significantly associated with children's blood lead levels in a logistic regression model. Similarly, Stark et al found that the condition of housing and the type of ownership were both significantly associated with children's blood lead levels.[38, 39] Clark et al also found that deteriorated housing was associated with higher blood lead levels among children and higher lead levels in paint and dust, but it was not clear from that study if children who lived in rental housing were at increased risk for having an elevated blood lead levels compared with children in owner occupied units.[31]

Single parent household also was significantly associated with children's blood lead levels in this study. Stark et al also found that single parent household was a significant risk factor for a child having a higher blood lead level; however their findings did not control for other risk factors.[39] In contrast, Bellinger et al did not find a statistically significant association between marital status and children's blood lead levels.[18] It is not clear why single parent household is a risk factor for a child having an elevated blood lead levels in this study. It may be that it is more difficult for one parent to supervise their children or that single parent household is confounded with socioeconomic status, or some unmeasured characteristic, to such an extent that the independent nature of the association observed in this study is in fact erroneous.

Strengths and Limitations of the Study

One strength of this study s that it included both Black and White children. Many of the earlier studies which measured children's environments primarily included either Black or White children, but not both.[3, 5, 12, 16] Also, this is one of the few studies that included a random sampling frame for contacting children; earlier studies often were based on convenience sampling. With the exception of one prior study, this is the only study in the United States which has examined the relation of dust lead and other environmental risk factors among urban children with low levels of blood lead levels.[15] Finally, in contrast with other studies, strict criteria were used in this present study to minimize lead exposure from sources other than the child's primary residence and dust samples were taken using detailed protocols so that comparison with subsequent studies is enhanced.

There are several limitations that should be noted. First, there was a limited range of dust lead levels and children's blood lead levels in this study. Thus, we are not able to provide precise estimates of the levels of dust lead associated with children's blood lead levels above 20 μg/dL or for floor dust lead levels above 40 μg/ft^2, for example. Second, despite our use of strict criteria, it is not possible to exclude children's exposure to lead from other unmeasured sources. Even if children spend less than 20 hours away from their primary residence each week, there may be exposure to lead from other sites or sources. Third, other potential modifiers of blood lead levels were not measured. It is known, for example, that calcium intake and the number of meals a child eats each day may affect lead absorption, yet we had no good measure of calcium intake or frequency of eating. A fourth limitation is that we only measured children's environments and blood lead levels during one season. Children's blood lead levels generally peak during the summer months, and it is possible that the blood lead and dust lead relationship varies during the year. Fifth, due to the strict criteria used in this study, the sample used in this study may not be representative of children in the United States or even in the city of Rochester. Thus, one cannot assume that the observed blood lead levels and dust lead relationship is valid for other populations without making certain assumptions. It also is possible that children who had high blood lead levels were excluded because they were previously identified through routine screening by their pediatricians and had received either environmental or medical intervention. If a large number of children were ineligible as a consequence of interventions associated with an elevated blood lead levels, the estimated slope between dust lead and blood lead levels would be attenuated in comparison to the true slope. Thus, the estimates of the slope presented in this paper are conservative.

Implications for a Dust Lead Standard for Residential Dwellings

There are at least two approaches that could be employed in developing a residential dust lead standard. The first is to estimate the daily intake of lead which would result from exposure to a given level of lead in surface dust. The second approach is to use epidemiologic data to infer a relationship between blood lead and dust lead levels.[23] Duggan and Inskip conclude that the epidemiologic approach, which was used here, is preferable because it is based on observation rather than speculation.[23]

The findings of this study suggest that a health based standard must first select a dust collection method and designate a specific surface(s) to be sampled. These data show that the slope is a function of the surface measured and of the collection method used to sample dust, and suggests that the wide range in the estimated slope of blood lead levels and dust lead found in previous studies is due, at least in part, to the use of different dust collection methods and the various surfaces measured.

In this analysis, logistic regression was used to model the relationship between various cut-off values for hypothetical dust lead standards and the proportion of children who have a blood lead level $\geq$ 10 µg/dL, adjusting for significant covariates. The proportion of children with blood lead levels $\geq$ 10 µg/dL in the United States population may be different than the estimates shown here following the promulgation of a dust lead standard. For example, the effect of setting a dust lead standard may or may not result in a truncation of the distribution of dust lead levels in housing units. Alternatively, the distribution of other significant covariates among children in the United States may be different than the distribution of these covariates among children in the Lead-in-Dust Study.

A dust lead standard for residential dwellings should consider both the level of dust lead that is dangerous to children and what level of dust lead is feasible to attain. It is unknown what proportion of housing units in the United States would fail a dust lead standard using either the wipe method or the BRM sampler. Therefore it is not clear whether it is feasible in the near future to regulate dust lead loading to a level consistent with the findings of this study, emphasizing the need to identify the proportion of housing units that have lead loading above various levels so as to determine the feasibility of compliance with a specific dust lead standard. Additional studies also are needed to confirm the findings of this study using similar protocols and dust collection methods.

Finally, our understanding of treatments to reduce lead loading or lead concentration in housing units is extremely limited. In the past, tri-sodium phosphate detergents have been recommended for dust control, but there are limited data comparing various types of detergents and it is not known whether dust control is effective in reducing blood lead levels in children who have low to moderately elevated blood lead levels. This study suggests that if we are to attain a significant reduction in blood lead levels in children who are exposed to lead-contaminated house dust, effective dust control measures are needed. Finally, it is also critical to demonstrate that dust control is efficacious in preventing or controlling childhood exposure to environmental lead in randomized trials.

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